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TOWARDS THE DEVELOPMENT OF ECOSYSTEM-BASED INDICATORS OF MANGROVES FUNCTIONING STATE IN THE CONTEXT OF THE EU WATER FRAMEWORK DIRECTIVE

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MANGROVE
BIOINDICATION
WFD
ECOSYSTEM-BASED MANAGEMENT
BENTHIC COMMUNITY

ABSTRACT. – European Water Framework Directive is enforced in five tropical French Oversea Territories where mangroves are present. Developing bioindication tools to support the ecosystem-based management approach of the Directive is needed. A series of expert workshops was organized and led to the proposal of a strategy and of an applied research program to develop bioindication tools. The proceedings of the workshops are presented as a case study, as this is the first time such an integrative ecosystem-based approach is proposed in mangroves, combining structural and functional aspects, from forest structure to benthic community functioning.

INTRODUCTION

Among environmental legislations aiming at reducing human impact on ecosystems, the European Water Framework Directive (WFD, 2000/60/EC) set the objective to reach "good ecological status" of coastal and transitional waters. Bioindication, status assessment of biological quality elements (BQE) in WFD terminology, is one of the means proposed to assess this ecological status. Bioindication tools must be developed in French Oversea Territories (OTs) as they are for continental Europe waters (Birk *et al*. 2012). As Marine Strategy Framework Directive (MSFD, 2008/56/EC) is not enforced in French OTs, WFD and its ecosystem-based management approach is the central tool for coastal and transitional waters management. French Guiana on the equatorial Atlantic coast of South America, Martinique, Guadeloupe and Saint Martin Islands in the Caribbean, Mayotte Island in the West Indian Ocean, are the five French OTs where both this environmental policy is enforced and where mangroves are present.

Mangroves are potentially subject to different kind of anthropogenic pollutions mediated by water: as an interface between land and sea, land-originated pollutions transit through, and as sediment deposition area, they are a sink for inorganic and organic contaminants. They are also sensitive to hydrological changes due to human activities. For this reason, it has been proposed to include mangrove ecosystem in the assessment of the ecological status of transitional and coastal waters, even if not identified among the standard WFD BQEs that have been mainly designed for non-tropical areas. This ecosystem-based approach is also currently applied for WFD bioindication tools development in coral reefs and seagrasses ecosystems (Le Moal *et al*. 2016)

Unlike mangroves at global scale, which have lost a third of their surface area in twenty years (Splading *et al*. 2010, Hamilton & Casey 2016) and are still in decline, the surface area of mangroves in the French OTs has been relatively stable over the same period (Roussel *et al*. 2009, Fromard & Proisy 2010, Jeanson *et al*. 2014). Nevertheless, available data on the pollution levels of these mangroves or their ecological status are very limited. The impact of the pollutions on mangrove ecosystem needs to be investigated and potentially operational bioindicators need to be identified. Beyond the ability to reflect the level and impact of pollution, the technical and financial feasibility to deploy either long-term monitoring or single diagnosis, is a crucial aspect of the bioindication tools.

In the scientific literature, numerous studies are assessing anthropogenic impact on mangroves, through different perspectives of interest and identify potential bioindicators defined as "physiological and biochemical responses to anthropogenic perturbation with consequences at different biological complexity levels, from species to ecosystem" (Mc Carty & Munkittrick 1996). But most of these studies are punctual, limited in time and space, deal with a single type of pollution, compare extremely contrasted sites *i.e*., pristine *vs* highly degraded, and focus on modifications observed in one or few compartments of the mangrove ecosystem through few parameters: soil organic matter composition (Aschenbroich *et al*. 2015), organic matter mineralization and primary production enhancement (Penha-Lopes *et al*. 2010, Molnar *et al*. 2014), soil heterotrophic community (Bouchez *et al*. 2013), crab population dynamics and feeding (Bartolini *et al*. 2009, 2011), RNA/DNA ratio in crabs (Amaral *et al*. 2009) or oxydative stress in oysters (Ramdine *et al*. 2012), shrimp population (Penha-Lopes *et al*. 2011), abundance of generalist *vs* specialist species of sponges (Díaz *et al*. 2004) or Bryozoa (Creary 2003), mudskipper population structure (Kruitwagen *et al*. 2006), mangrove tree leaves pigment concentration (MacFarlane & Burchett 2001; MacFarlane 2002) and respiration (Herteman *et al*. 2011), canopy and tree community structure (McDonald *et al*. 2003, Lovelock *et al*. 2009, Herteman *et al*. 2011), tree productivity (McDonald *et al*. 2003) or mortality (Duke *et al*. 2005, Schaffelke *et al*. 2005) for instance (see Dirberg 2015a for a review). Choosing among them the most relevant ones to be used and deployed in the WFD's integrative ecosystem approach to assess ecological status is not straightforward:

– There is a variety of situations both within and between our five OTs of interest: anthropogenic pressures, mangroves types, associated biota, and ecological conditions are diverse;

– The complexity of the ecological status apprehension in mangrove ecosystem requires an holistic transdisciplinary approach;

– The stakes associated with the cost and mandatory implementation of environmental policy are high.

For these reasons, a transdisciplinary panel of experts from diverse scientific and environmental management background, was gathered and asked to set up a strategy to develop bioindication tools for WFD water bodies ecological status assessment in French overseas mangroves. This is a joint initiative from the French Biodiversity Agency (OFB) and the National Museum for Natural History (MNHN), with experts from French National Center for Scientific Research (CNRS), French National Research Institute for Sustainable Development (IRD), Aix-Marseille University, Toulouse University, Conservatoire du Littoral, Nantes University, French geological survey (BRGM), and University of the French Antilles.

This paper summarizes, as a case study, the proceedings and the proposed strategy from the expert group

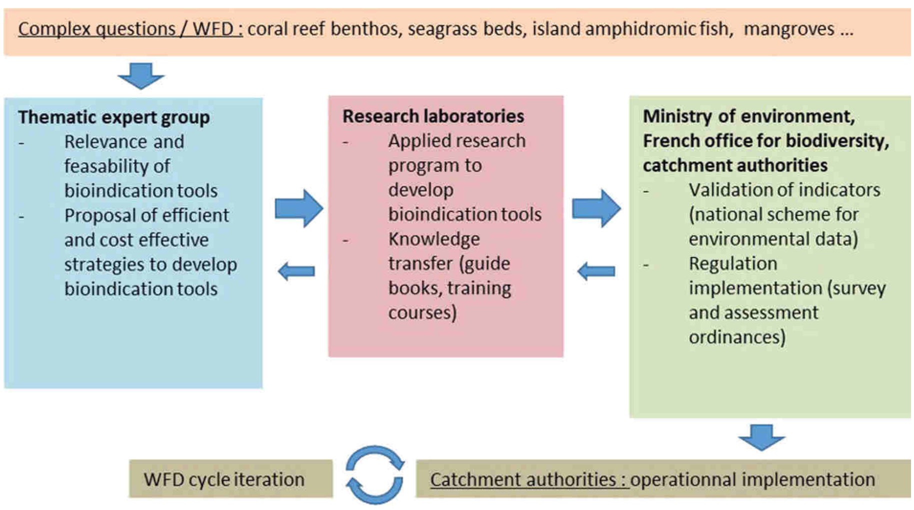

Fig. 1. – Scheme of the general organization of WFD bioindication tools development for French OTs.

workshops that led to the deployment of a 5-year transdisciplinary research program on bioindication in mangroves ("Thematic expert group" box and first part of "Research laboratories" box on Fig. 1). This developmental phase will allow field sampling and analysis. First bioindication tools are expected to be available at the end of this phase for routine deployment by either private engineering consulting, national or regional public environmental agencies or research laboratories.

Two 3-days workshops, gathering 14 and 16 people, were held in Paris in September 2015 and May 2016 at National Museum of Natural History.

EXPERT GROUP WORKSHOPS PROCEEDINGS

Building the context of the expertise

The main objective of the first workshop was to bring everybody to a common level of knowledge on WFD requirements and share views on this issue from the perspective of the different expert's background.

1) A bibliographic review on bioindication in mangroves (Dirberg 2015a) was prepared and sent to the participants to prepare the first workshop.

2) A presentation and discussion of the conceptual framework of the WFD were organized as it raises immediately many questions to any person who is not already acquainted with it and its vocabulary. Going through the process of questioning and sharing thoughts on the WFD concepts and objectives, even if it does not seem to deliver measurable results, can be seen as a very good mean to build a first common agreement. Hence for pragmatic reasons, and as first common decision, questions about the definition of "good" when talking of "good ecological status" (of which we cannot ignore the political and philosophical dimension), the possibility to find or define reference conditions, the relevance of the WFD water bodies delineation from mangroves perspective, the possibility to untangle the contribution of different anthropogenic pressures, or global change, when facing ecological impact, were discussed and acknowledged as problematic. But it was decided they should not hamper the main objective to develop tools for helping to maintain or improve ecological status of mangrove ecosystems. These questions will be kept in mind and reformulated as the project evolves.

Focussing on anthropogenic pressures allows sharing transdisciplinary knowledge and experience, and delivered first important results: (i) Identification and prioritization of known or potential anthropogenic pressures affecting mangroves in each OT (Dirberg 2015b); (ii) Description of how these pressures could affect any component of the mangrove ecosystem and identification of parameters that would vary with the impact in a predictable way; (iii) Identification of potential sampling sites in each OT, sites either known to be impacted, or as little disturbed as possible to be considered reference sites.

This process does not allow to limit significantly the number of parameters that are potentially relevant bioindicators, but it clarifies the needs, the constraints, the background and hence the possibilities in each of the OTs of interest.

Setting the practical objectives

The second workshop objective was to choose the parameters to be measured in the field and set up the strategy to develop the bioindication tools.

As the final objective was to assess the "ecological status of the waters through bioindication in the mangroves", we needed to define explicitly what objects we were actually looking at. Thus, the concept was broken down in a list of more practical and explicit descriptors, structural and functional, to characterize the ecological status of a mangrove itself:

– Forest structure dynamics;

– Mangroves tree growth;

– Regenerative capacity of the ecosystem;

– Species abundance and diversity (species with a life trait depending on mangroves);

– Functional characteristics of the sediment (in particular the organic matter degradation process);

– Eutrophication signs.

In the WFD perspective, to be qualified these descriptors will have to be compared to a reference, either historical or theoretical. Beyond these descriptors that allow assessment of the present mangrove status, two vulnerability descriptors are proposed to be added to take into account the context and its expected evolution:

– Vulnerability to sea level rise (*i.e.*, landward accessibility to mangrove migration);

– Vulnerability to foreseen urban / agricultural / industrial development.

For each descriptor, potential parameters among those sensitive to the anthropogenic pressure identified at the first workshop, and associated methods, could be proposed, but many other considerations on scientific, technical, organizational and financial issues were considered:

– As the response time to pressures is highly dependent on the level of biological complexity (from the biochemistry of a single organism, to community or ecosystem levels, from fast to slow) and as this biological levels are observed at very different spatial scales (see Martínez-Crego *et al*. 2010), the combination of methods proposed to give information on the descriptors should cover different spatio-temporal scales, from station to river basin, from season to decade.

– For mangrove forest, mangroves trees and macrofauna species descriptors, we can find robust methodologies in an extensive literature and no further development seems necessary. There is less literature on the functional characteristics of the mangrove sediment and organic matter degradation pathways and dynamics (Molnar *et al.* 2013, Luglia *et al.* 2014, Pascal *et al.* 2014, Aschenbroich *et al.* 2015, David *et al.* 2019 for instance) and none presents an integrative approach including benthic macro- and meiofauna, fungi and prokaryotes within the same study. This benthic community has a pivotal role in mangrove ecosystem functioning (Nagelkerken *et al.* 2008; Aschenbroich *et al.* 2016, 2017). Therefore, we must pay particular attention to this compartment and its functional aspect in the development phase of our bioindication tools. Finally we found only one publication (Carugati *et al.* 2018) that attempts to combine a set of parameters covering our different descriptors in an integrative ecosystem-based approach to assess biodiversity and ecosystem functioning related to mangrove degradation. This case study compares highly contrasted mangrove sites, one pristine and the other with a massive dieback, and does not link the observed impact on functioning and biodiversity to any specific pressure. We must be able to establish links between pressure and impact for management purposes and we must be able to assess status not only in extreme degradation situations (as this is not the usual situation) but also in situations of moderate pollution.

– For the developmental phase of the project, a common standard data set from the different OTs is needed hence deploying the same sampling strategy and methods in this different ecological contexts and species assemblages.

– More parameters than those that will be retained beyond the developmental phase of the project need to be investigated, in order to have an in-depth view and then be able to choose the most relevant ones. Pollution levels must be measured in situ, as water sampling sites monitored under the WFD for assessment of chemical status do not provide adequate information to allow linking impacts to pressures.

– Potential reference sites are difficult to find, and may not exist, as in Mayotte, Martinique and Guadeloupe, population is dense and human activities are everywhere. The least impacted sites will serve as reference sites for the development phase. Reference for the final WFD status assessment will have to be define. Sites on other islands of the region could be considered. A review of archeozoological records of species known to be linked to mangroves is also proposed to provide some historical context and tackle the shifting baseline syndrome.

– In French Guiana, human population density is much lower and access to mangroves is more difficult. Coastal mangroves are highly dynamical, depending on the Amazon River sediments loadings (Fromard *et al.* 2004, Anthony *et al.* 2010). On the contrary, estuarine mangroves inland along the polyhaline area show different vegetation structure and are more stable (Fromard *et al.* 2004) but are probably also more affected by local anthropogenic pressures. The mangrove along the coast is more directly affected by the Amazon River discharge. Hence the anthropogenic pressures they are facing are out of control of French authorities and are not considered within WFD perspectives. Therefore, only estuarine mangroves are here targeted and the mangrove sampling sites were chosen, in a first time, along the Cayenne estuary, moving away from Cayenne, the main city of French Guiana.

– We need to choose carefully the sampling stations to limit as much as possible the ecological conditions discrepancies between samples and maximize the signal that could be linked to the different levels of pollution. This means:

• Choosing sites within similar mangrove zonation: riverine *Rhizophora* zonation in French Guiana, either *Bruguiera* or *Rhizophora* dominated zonation in Mayotte, seaward *Rhizophora* zonation in Martinique and Guadeloupe;

• Measuring *in situ* the tidal level and immersion time to ensure the comparability;

• Core sampling in similar conditions: anticipate underground roots distribution and crab burrows to avoid them, take into account soil micro-topography to avoid local low points with potentially very different immersion time.

– Mangrove macrofauna: crustacean, molluscs, insects, birds but also sessile Bryozoa, sponges, ascidians, and other taxa could be potentially bioindicator, but we lack ecological knowledge on most of them, and the necessary work required to fill the gaps is not compatible with timeframe and budget allowed for this project. Benthic invertebrates (meio-, meso- and macrofauna) living within sediments and their bioturbation functional roles (Aschenbroich *et al.* 2017) were prioritized in this study since they are known as bioindicators for the WFD in temperate areas. As crabs are key engineer species in mangroves (Kristensen 2008), minimal information should be collected. As cryptic and burrowing animals, crabs can be difficult to monitor (Kent & McGuiness 2006). Thus, crabs burrow counting (Skov *et al.* 2002) with measurement of opening size of burrows (Micheli 1991) was proposed as a minimum proxy to crabs abundance.

– Among technical constraints, we need to be able to go to the field, with one small boat, one or two cars, hence not too many people, collect samples for different type of analysis, make *in situ* measurements, bring back the samples in good conditions, and allow time for the subsampling, measurements and sample preservation at laboratory.

– Temporal and spatial natural variation of the different parameters cannot be tackled at the same time we were sampling for testing the full set of parameters. This has to be done in a second phase with a dedicated sampling strategy. The first phase should allow reducing the num-

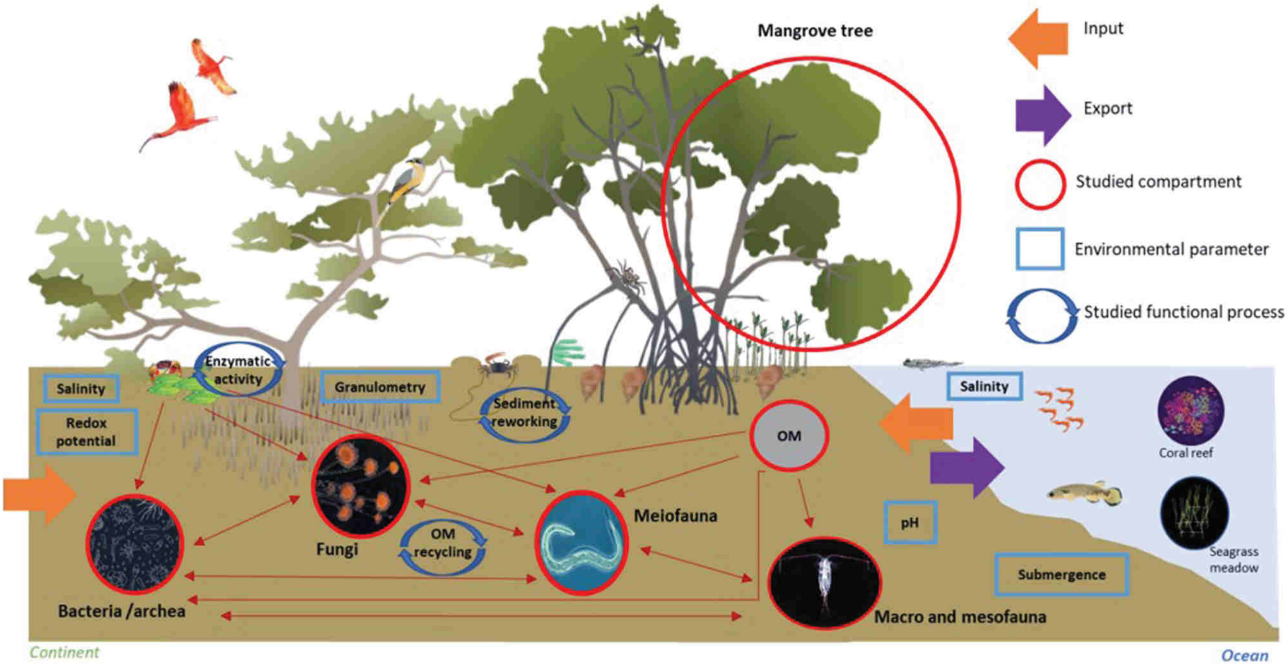

Fig. 2. – Simplified conceptual scheme of the studied compartments and functional processes of mangrove ecosystem toward the development of ecosystem-based indicators of mangroves functioning state (Figure credit: Maud Fiard).

ber of necessary measured parameters and come out with a lighter field protocol for this second phase.

– The lack of research facilities or equivalent accessible laboratory workspace in Saint Martin excluded it from the first round of sampling.

The resulting choices as a research program

The sums of the needs and constraints led to the proposal of a strategy (Dirberg 2017) that became an applied research program. We summarize the content of this program as a result of the presented expertise process (Fig. 2). Protocols will be detailed in dedicated publications.

Sampling sites

In each of the four sampling OTs, sampling sites were proposed by local experts. The sampling team visited the sites prior to sampling to confirm the selection and checked the accessibility in reasonable distance/time/conditions from the laboratory, and that ecological conditions were similar.

Hence, we have chosen 3 sites in French Guiana along the Cayenne river, 4 sites in Martinique, 5 sites in Guadeloupe, 2 *Rhizophora* dominated sites and 3 *Bruguiera* dominated sites in Mayotte, making 17 sites in total (Table I). These sites are either affected by different type of known pressures (agricultural, industrial, domestic waste) or potential local reference.

Studied parameters

The final choice of studied compartments and parameters is compatible with a dense one station-a-day organization with 5 peoples, one boat, two cars.

In situ measurement

Environmental parameters:
– Pore water salinity
– Water level recording (HOBO probe)

On sediment core samples

On each station, 3 cylindrical sediment cores were sampled (10 cm diameter, 18 cm in length), sliced at the lab for subsampling (10 slices: 0-1-2-4-6-8-10-12-14-16-18cm). On each slice, following parameters were measured:

Potential bioindication parameters:

– Sediment reworking measurement (one-week incubation after fluorescent tracers deposit) as a proxy of endofauna activity.

– Biomass, abundance, diversity of microbes and fungi (genetic tools).

– Diversity, density and biovolume of small macrofauna.

– Diversity, density, and biomass of meiofauna.

– Potential enzymatic activity measurement (Biolog Ecoplates®) tested as a potential integrative bioindication tool.

Table I. – GPS coordinates (WGS84) of the 17 sampling stations.

Site	Station	st_code	Latitude	Longitude	Station type / pressure
French Guiana	Crique Fouillée	S1	4.914780	–52.337759	Urban
French Guiana	Confluence	S2	4.897008	–52.374365	Low, domestic
French Guiana	Petit Cayenne	S3	4.858881	–52.399868	Reference station
Mayotte	Dembéni1	DS	–12.844892	45.194823	Urban
Mayotte	Dembéni2	DP	–12.837679	45.190321	Reference
Mayotte	Malamani1	MS	–12.921955	45.152809	Sewage water
Mayotte	Malamni2	MP	–12.923628	45.152893	Local reference
Mayotte	Zidakani	ZI	–12.785458	45.096780	Reference ?
Martinique	Baie du Trésor	S4	14.766701	–60.883034	Reference
Martinique	Pointe Marin	S5	14.447821	–60.878443	Sewage
Martinique	Pointe Merle	S6	14.561594	–61.010904	Agriculture
Martinique	Cohé du Lamentin	S7	14.602466	–61.021394	Urban/industrial
Guadeloupe	Intermédiaire	IN	16.2775	–61.5488	Urban
Guadeloupe	Décharge	DE	16.2594	–61.5469	Landfil site, Urban
Guadeloupe	Babin	BA	16.3388	–61.5294	Reference
Guadeloupe	Fajou	FA	16.3509	–61.5906	Reference
Guadeloupe	Goyave	GO	16.1379	–61.5743	Urban, Agriculture

– Biochemical tracers' concentration and/or ratio (fatty acids, pigments) as a proxy of organic matter degradation processes.

Environmental parameters:

– Physical: Redox potential, pH, sediment granulometry, pore-water salinity.

– Chemical: organic contaminants (PAHs, PCBs, pesticides, phthalates, PBDE, alkylphenols) and inorganic contaminants (heavy metals), C:N ratio**.**

On litter bags

On each station, litter bags filled with 10 *Rhizophora* leaves, deposited on site and then sampled at 0, 5, 10, 20, 30 days or 0, 7, 14 days.

Potential bioindication parameters:

– Biomass, abundance, diversity of microbes and fungi (genetic tools).

– Potential enzymatic activity measurement (Biolog Ecoplates®) tested as a potential integrative bioindication tool.

– Biochemical tracers' concentration and/or ratio (fatty acids, pigments) as a proxy of organic matter degradation processes.

Forestry quadrats

Potential bioindication parameters and environmental parameters:

– Tree species and density.

– Tree diameter measurement.

– Tree sanitary status.

– Saplings counting.

Crabs burrows quadrats

In three 1 m^2 quadrats, measurement of each burrow aperture width to the closest centimeter as proxy of crabs abundance.

Remote sensing

Characterization of soil occupation of the catchment upstream each mangrove site.

Delineation of mangroves for long term monitoring

CONCLUSION

WFD represents an important opportunity both for environmental management and for scientific research. As illustrated in this case study, ecosystem-based management sets a real challenge to science as understanding the complexity of mangrove ecosystem and taking into account functional parameters are necessary to develop the bioindication tools. This has led to the development of a transdisciplinary research project that might have not been possible without this impulse. Bringing together experts from very different cultures and professional goals, and getting them to build together a project that meets the standards of academic research and the needs of environmental managers, is also a challenge, but is necessary in the context of environmental policy implementation and ecosystem-based management. Finally, another important by-product of the process presented here, is the increased exchange between science and management, the mutual understanding of each other's needs, the increase in experience, knowledge and of concerns of everyone, that ecosystem-based management stimulates.

The first phase of the transdisciplinary applied research project described here should end in 2021. Sampling in French Guiana occurs in 2017, Martinique and Mayotte in 2018, Guadeloupe in 2019. First scientific results are under the process of publication. Environmental managers and scientific researchers will meet several times by 2021 to discuss the results and the opportunity to transfer them into WFD long term monitoring.

Ecosystem-based approach is a management standard within other EU environmental policy like Main Strategy Framework Directive (MFSD) and leads to the development of dedicated Ecosystem-Based Quality Index methods (Boudouresque *et al*. 2015, Thibaut *et al*. 2017). From a WFD perspective as developed in France, the integrated ecosystem approach developed in French OTs and illustrated here for mangroves, is new. It is justified by the complexity of tropical ecosystems and the relative lack of knowledge, compared to European lake and river ecosystems for instance. This study is providing some basic knowledge that was lacking on French OTs mangroves. And, from a global perspective, it is the first attempt to combine all these structural and functional parameters, in an integrative ecosystem-based approach for ecosystem-based management.

ACKNOWLEDGEMENTS. – This work is financially supported by Office Français pour la Biodiversité, Office de l'Eau de Guyane, Office de l'Eau de Martinique, Office de l'Eau de Guadeloupe. The field sampling was permitted thanks to the lab support of USR LEEISA / Centre IRD-CNRS de Guyane, CUFR de Mayotte, Laboratoire de biologie marine de l'Université des Antilles à Pointe-à-Pitre, CIRAD de Martinique. This work has benefited from an "Investissements d'Avenir" grant managed by Agence Nationale de la Recherche (CEBA, ref. ANR-10-LABX-25-01).

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